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## **Prevalence of complications in intraoperative magnetic resonance imaging combined with neurophysiologic monitoring**

Sarnthein, Johannes ; Lüchinger, Roger ; Piccirelli, Marco ; Regli, Luca ; Bozinov, Oliver

**Abstract:** BACKGROUND AND OBJECTIVE High-field intraoperative magnetic resonance imaging (ioMRI) is becoming increasingly available in neurosurgery centers, where it has to be combined with intraoperative neurophysiologic monitoring (IONM). IONM needle electrodes remain on the patient during ioMRI and may cause image distortions and burns. We tested magnetic resonance (MR) -heating experimentally and investigated the prevalence of complications. METHODS We studied electrodes that are certified for IONM, but not "MR conditional." They consist of copper cables (length, 1.5 m) and needles made of either stainless steel (ferromagnetic) or paramagnetic platinum/iridium alloy. We simulated an ioMRI session with gel and measured the temperature increase with optical fibers. We measured the force that an electrode experiences in the magnetic field. Between 2013 and 2016, we prospectively documented subcutaneous needle electrodes that remained in the patient during intraoperative 3 Tesla ioMRI scans. RESULTS The in vitro testing of the electrodes produced a maximum heating ( $\Delta T = 3.9^{\circ}\text{C}$ ) and force of 0.026 N. We placed 1237 subcutaneous needles in 57 surgical procedures with combined IONM and ioMRI, where needles remained in place during ioMRI. One patient suffered a skin burn on the shoulder. All other electrodes had no side effects. CONCLUSIONS We have corroborated the history of safe use for electrodes with 1.5 m cable in a 3T MRI scanner and demonstrated their use. Nevertheless, heating cannot be excluded, as it depends on location and cable placement. When leaving electrodes in place during ioMRI, risks and benefits have to be carefully evaluated for each patient.

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1 Prevalence of complications in intraoperative MRI combined with neurophysiological  
2 monitoring.

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20 Short title: ioMRI combined with IONM

## 21 22 DISCLOSURE

23 The authors report no conflict of interest concerning the materials or methods used in this  
24 study or the findings specified in this paper.

25 JS has given presentations for Inomed and OB has given presentations for Siemens.

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## ABSTRACT

Background: High field intraoperative MRI (ioMRI) is becoming increasingly available in neurosurgery centers, where it has to be combined with intraoperative neurophysiological monitoring (IONM). IONM needle electrodes remain on the patient during ioMRI and may cause image distortions and burns.

Objective: We tested MR-heating experimentally and investigated the prevalence of complications.

Methods: We studied electrodes that are certified for IONM, but not “MR conditional”. They consist of copper cables (length 1.5 m) and needles made of either stainless steel (ferromagnetic) or Pt/Ir (paramagnetic). We simulated an ioMRI session with gel and measured the temperature increase with optical fibers. We measured the force an electrode experiences in the magnetic field. We prospectively documented subcutaneous needle electrodes between 2013-2016 that remained on the patient during intraoperative 3 Tesla ioMRI scans.

Results: The in-vitro testing of the electrodes produced a maximum heating  $\Delta T = 3.9^{\circ}\text{C}$  and force of 0.026 N. We placed 1237 subcutaneous needles in 57 surgical procedures with combined IONM and ioMRI, where needles remained placed during ioMRI. One patient suffered from a skin burn at the shoulder. All other electrodes had no side effects.

Conclusions: We have corroborated the history of safe use for electrodes with 1.5 m cable in a 3T MR scanner and demonstrate their use. Nevertheless, heating cannot be excluded, as it depends on location and cable placement. When leaving electrodes in place during ioMRI, risks and benefits have to be carefully evaluated for each patient.

### Keywords:

Intraoperative Neurophysiological Monitoring; intraoperative MRI; RF heating; magnetic force; diamagnetic metal; paramagnetic metal; ferromagnetic metal; electrode cable length

### Short title:

ioMRI combined with IONM

## 1. INTRODUCTION

In tumor neurosurgery, minimizing residual tumor mass prolongs overall survival of the patient (1). Intraoperative imaging techniques are constantly expanded to minimize tumor remnants left unresected. While 5-ALA (2) and ultrasound (3) are easily available, high-field intraoperative MRI (ioMRI) is not yet widespread. For maximal safe resection in the vicinity of eloquent areas, intraoperative neurophysiological monitoring (IONM) has been continuously advanced (4-7). There are fewer severe neurological deficits and more extensive resections within eloquent regions when IONM is used (5). IONM of the motor system involves the placement of subcutaneous needle electrodes in or near the muscles of interest. Electrodes remaining on the patient during ioMRI scans may lead to image distortions and tissue heating under certain conditions, which may also occur in concurrent EEG and MRI (8-12). These effects depend strongly on needle shape and material, on needle location and direction, magnet strength, imaging sequence and the length and layout of the electrode cables (9, 11-15). There are no IONM electrodes with label «MR conditional» and usage of IONM electrodes during ioMRI is always «off-label». In a previous publication we have shown that needle electrodes made from a paramagnetic material like Pt/Ir cause less image distortion in a 3T MRI than ferromagnetic stainless steel needles (8). To contribute to a «history of safe use» of needle electrodes in ioMRI, we conducted in-vitro tests of force and RF heating, and investigated the prevalence of complications.

## 2. PATIENTS AND METHODS

### 2.1. Subcutaneous needle electrodes

Scalp electrodes for EEG and TES consisted of platinum/iridium alloy (paramagnetic Pt/Ir 0.4 x 12 mm straight needles, diamagnetic copper cable length 1.5 m, [www.inomed.com](http://www.inomed.com), part 529500). If needed, we fixated the Pt/Ir electrodes with skin staplers (ferromagnetic stainless steel, Appose ULC auto suture 35 W, Covidien, [www.medtronic.com](http://www.medtronic.com)). To record muscle activity, we used twisted-pair non-insulated straight needle electrodes placed subcutaneously (ferromagnetic stainless steel, 0.4 x 12 mm, Neuroline twisted pair, copper cable length 1.5 m, [www.ambu.com](http://www.ambu.com), Figure 1). Impedance was typically below 5 k $\Omega$ .

### 2.2 In-vitro test of RF heating during 3T MR imaging

To test possible heating of electrodes during MR imaging, we set up an experiment in the 3T MR scanner (Figure 2). The experiment was conducted following the guideline ASTM Standard F2182-11A “Test Method for Measurement of Radio Frequency Induced Heating On or Near Passive Implants During Magnetic Resonance Imaging” (14). While the test standard was developed for passive implants completely inside the body, we here adapted it for our electrodes. We tested the twisted pair electrode (Figure 1). We fixed the temperature sensor fiberoptic Neoptix® to the electrode tip. We first applied the MR sequence T2 turbo spin echo in transverse axis with 49% predicted head-SAR (1.5 W/kg) to replicate the condition during surgery. We then modified the T2 sequence to 99% predicted head-SAR (3.2 W/kg) to enlarge the energy deposition and temperature increase.

### 2.3 In-vitro test of magnetic force in the 3T MR scanner

We measured the deflection of the electrode at the location of the highest magnetic field gradient and calculated the magnetic force on the needle.

### 2.4. Patient selection

The study was performed prospectively in all consecutive patients who received IONM during surgery and where subcutaneous needle electrodes were left on the patient during ioMRI between 01/2013 and 02/2016. The study was approved by the IRB (KEK-ZH 2012-0212) and informed consent was waived. We included a total of 57 surgical procedures in 42 adult patients (11 females, mean age 46 y, range 18 y - 73 y) and in 15 children under 18 years (4 females, mean age 8 y, range 18 mo - 14 y). Diagnoses were: astrocytoma (23), glioblastoma (12), oligodendroglioma (8), ependymoma (2), epidermoid cysts (2), pituitary adenoma (2), STA-MCA bypass (2), and one patient each with medulloblastoma, chondrosarkoma, Rathke's cleft cyst, cervical schwannoma, giant aneurysm or cavernoma. In a prior study (8) we reported on the first 13 patients of the current study and image distortions for 3 needle types. We now report on more patients, include new analyses of electrode numbers, in-vitro testing of heating and force, and an adverse event.

### 2.5. Anesthesia management

Following the standard protocol for neurosurgical interventions, anesthesia was induced with intravenous application of Propofol (1.5 - 2 mg/kg) and Fentanyl (2-3 µg/kg); the intratracheal intubation was facilitated by Atracurium (0.5 mg/kg). Anesthesia was maintained with Propofol (5-10 mg/kg/h) and Remifentanyl (0.1-2 µg/kg/min).

## 2.6. Modalities of IONM and sites for recording muscle activity

In the series of surgeries presented here, the modalities of IONM included free-running electromyogram (EMG), sensory evoked potentials (SEP) from the median nerve and motor evoked potentials (MEP). For MEP, we recorded muscle activity from thenar muscles and the abductor digiti minimi muscle of the hand and, if necessary, the flexor hallucis brevis muscle. Among cranial nerve (CN) target muscles we recorded from superior rectus muscle for CN3, the superior oblique muscle for CN4, the masseter muscle for CN5, the lateral rectus muscle for CN6, orbicularis oculi muscle, orbicularis oris muscle, and mentalis muscle for CN7, the soft palate for CN9 and the genioglossus muscle for CN12. Target muscles were chosen to meet the monitoring modalities required by the surgeons (LR, OB) and electrodes were placed by the IONM staff.

## 2.7. Intraoperative 3T MR imaging (ioMRI)

When positioning the patient, the head was fixed in a Noras OR Head Holder (part number 112685, [www.noras.de](http://www.noras.de)). When preparing for intraoperative 3T MR imaging, we followed our standard operating procedures: We placed sterile sheets over the wound, attached the upper part of the head coil, disconnected all cables from the monitoring device, and assured that cables had no direct skin contact and that cables were aligned in parallel to the main magnetic field to minimize electric current induction by the radio frequency (RF) field (Figure 3).

The patient was then transferred to a room adjacent to the surgery theatre and shifted into the bore of the MR (3T Siemens Magnetom). In the MRI head scans described in this study, the region of the RF transmit coil included the patient down to the chest. Recording time summed up to about 35 minutes (Table 1). Recording sequences with the highest specific absorption rate (SAR) were T2 scans with  $SAR = 1.52 \text{ W/kg}$ . Together with preparation and transfers this added about 1 hour to the total duration of surgery. After surgery, the site of each electrode was examined visually for skin irritations (JS, LR, OB).

## 2.8 Statistical methods

We used descriptive statistics only.

### 3. RESULTS

#### 3.1 In-vitro testing of RF-heating

Within the limits of our standard operating procedures for surgery, we tested several geometric configurations of the needle position and cable alignment and present here the worst-case scenario (Figure 2A). With the MR sequence in clinical use ( $SAR = 1.52 \text{ W/kg}$ ), heating did not exceed  $\Delta T = 0.7^\circ\text{C}$  in our experiment. Next, we increased the RF field resulting in  $SAR=3.2 \text{ W/kg}$  and explored several variations of the electrode setup. For one setup, the twisted pair electrode with 1.5 m cable was heated by  $\Delta T = 3.9^\circ\text{C}$  (Figure 2B).

#### 3.2 In-vitro testing of the magnetic force on the ferromagnetic needle

At the location of the highest magnetic field gradient (30 T/m), the ferromagnetic needle was deflected by  $15^\circ$  from the vertical. The weight of the needle was 2.6g. The force exerted by the magnetic field amounted to 0.026 N.

#### 3.3. Number and types of electrodes left in ioMRI

We placed a total of 1093 electrodes in 57 surgeries. Of these, 301 were Pt/Ir electrodes for EEG and TES placed on the scalp. 246 were stainless steel electrodes placed above the chest to record muscle activity and for electrical grounding. Target muscles of CN3 were recorded in 1 surgery, CN4 in 2, CN5 in 1, CN6 in 14, CN7 in 34, CN9 in 5, CN11 in 1, CN12 in 10. The other 690 electrodes were placed below the chest to record muscle activity and to stimulate median and tibial nerves for sensory evoked potentials. The electrodes were left on the patient during ioMR imaging.

#### 3.4. Occurrence of an adverse event

There were no adverse events for the ferromagnetic twisted pair stainless steel needles. There was one adverse event for the paramagnetic Pt/Ir needle, where a skin burn (first degree) was observed postsurgically at the site of the ground electrode at the shoulder (Figure 4). The site of the skin burn lets us assume that it was most likely caused by heating of the electrode tip. The electrode was a Pt/Ir needle with a 1.5 m copper cable. The lesion healed within 7 days without scarring.

#### 3.5. Image distortion by skin staplers fixating Pt/Ir needles

In all surgeries we observed localized image distortions on the skin at the needle sites, which also slightly affected the image of the adjacent skull (Figure 5). The distortions were

due to the ferromagnetic skin staples. This kind of distortion did neither affect the course of surgery nor disrupt neuro-radiological diagnostics and was therefore not investigated further.

## 4. DISCUSSION

In this study we describe in-vitro testing of force and heating in MRI and a series of procedures where IONM electrodes were left on the patient during ioMRI. For these 1.5 m cable electrodes, the prevalence of adverse events was in the ‰ range (1/1093).

### 4.1 Force on ferromagnetic needle electrodes

The stainless steel needles used for IONM are very small and lightweight. Our in-vitro measurement of the force in a worst-case scenario resulted in a small force (0.026 N), which is easily absorbed by the adhesive strips used for fixation. This is in line with our intraoperative observation, that none of the patients suffered from skin problems due to electrode movement.

### 4.2. Heating in ioMRI

In general, heating due to the RF field can occur (9, 13). In agreement with the literature (12), the adverse event due to heating in the RF field was irrespective of the electrode material used. However, heating depended strongly on cable length and on the geometrical alignment of the cable (Figure 2).

In our case with the skin burn (Figure 4), the electrode was placed in the shoulder region. This electrode was outside the head coil, but still partially inside the RF body coil which is responsible for the heating effects. With an electrode on the shoulder the cables may be even nearer to the rods and end ring of the body coil, compared to cables coming from the face, where the shorter part of the cable inside the body coil may be compensated by the stronger E-fields near the RF body coil. No RF heating can be expected for electrodes which are placed below the chest because there the electrical field of the RF body coil is strongly reduced.

### 4.3 General considerations and recommendations

Leaving IONM subcutaneous needles on the patient during ioMRI can be acceptable despite the lack of IONM needles labelled “MR conditional”. Even though we could not show any heating >3.9°C after 15 min, this does not exclude the possibility of much higher heating. Local SAR variation on the surface of the patient may further influence the results (15).



Clearly, MR sequences with lower SAR bear smaller risks of burns. If IONM electrodes are used within the RF body coil or in the near neighborhood, the potential risk of RF heating must be taken into account and the medical benefit must outweigh the risk.

During surgery, clear guidelines were followed to reduce the potential risk of RF heating (Figure 3, Table 2): it was assured that cables had no direct skin contact (isolation should be at least 1 cm); that cables were aligned in parallel to the main magnetic field; that cables of multiple electrodes did not cross each other; and that the connectors were isolated against each other and against the skin (to avoid nerve stimulations from the gradient).

Contrary to popular belief, heating can occur with both ferromagnetic and diamagnetic materials, since heating is due to the electric conductivity of the needle and cable, which is high for stainless steel and Pt/Ir compared to the tissue conductivity. Paramagnetic materials like Pt/Ir are preferred on the scalp where image distortions may be critical for surgical planning.

If the exact placement site is not critical, like for a ground electrode, the RF region of the transmit coil should be avoided, i.e. the needle should be placed below the chest or in case of smaller children at least 0.5 m out of the isocenter (Figure 3). Likewise, it should be preferred to place needles in well-perfused tissue.

One could consider removing IONM electrodes before ioMRI. However, IONM is most important for a safe surgery at the final stage of resection, which will be after ioMRI in critical cases. To benefit from IONM at the final stage, one would have to re-install IONM needles after ioMRI, which is prevented by sterility requirements.

Improved IONM needles would reduce RF heating with cable traps or with filters just behind the needle (9, 10), e.g. by a resistor in the handpiece of the electrode. Alternatively, a short cable - with the connector only a few cm from the needle - would also reduce RF heating. It would be welcome if “MR conditional” electrodes were developed for IONM.

#### 4.4 Limitations of the study

The in-vitro test of electrode heating did not achieve a relevant temperature increase for the MR sequence in clinical use. But we could show that with modification of cable placement, RF heating effects can strongly increase. It cannot be excluded that configurations which are within the local guidelines for cable placement will reach similar heating.

All findings were obtained for a 3T scanner and may not be applicable for units with lower or higher fields.

## 5. CONCLUSIONS

We have corroborated the history of safe use for electrodes with 1.5 m cable in a 3T scanner. Nevertheless, heating cannot be excluded, as it depends on location and cable placement. When leaving electrodes in place during ioMRI, risks and benefits have to be carefully evaluated for each patient.

## 6. FIGURE LEGENDS

Figure 1. Tip of twisted pair stainless steel electrode. The Pt/Ir electrode has the same shape but is not paired.

Figure 2. In-vitro testing of RF heating. (A) Experimental setup. An electrode tip of the twisted pair electrode with 1.5 m cable (red-black) was attached to a temperature sensor Fiberoptic (yellow, Neoptix®). A plastic jar (volume 1.5 l) was filled with a convection-free gel and placed in the receive head coil. The needle of the electrode was placed in the gel and the cables were aligned in parallel to the axis of the bore. An additional temperature sensor was placed directly in the gel as a reference. (B) Temperature measurement. During the MR sequence with SAR = 1.5 W/kg there was no discernible temperature increase. During the MR sequence with SAR = 3.2 W/kg, the temperature at the electrode tip (red curve) increased but not at the reference sensor (blue curve). After 853 sec (14 min) the tip had reached a heating of  $\Delta T = 3.9^{\circ}\text{C}$ . The heating depended strongly on the geometry of the cable and we present here the worst-case scenario. With the MR sequence in clinical use (SAR=1.52 W/kg), heating did not exceed  $\Delta T = 0.7^{\circ}\text{C}$  in our in-vitro testing.

Figure 3. Position of electrodes and their cables during ioMRI recordings. All cables were aligned in parallel to the main magnetic field. Gauze pads were used to assure that cables had no direct skin contact.

Figure 4. First degree skin burn (arrow) at the electrode site on the patient's shoulder (male, 12y), depicted after removal of the electrode.

Figure 5. Intraoperative MR image (coronal plane, male, 5y).

Image distortion on the skull from skin staplers, which fixate Pt/Ir electrodes at sites C3, Cz, C4 (top arrows). No electrode movement, no skin irritation and no heating were observed at these sites. The site of image distortion is far from the lesion (bottom arrow).

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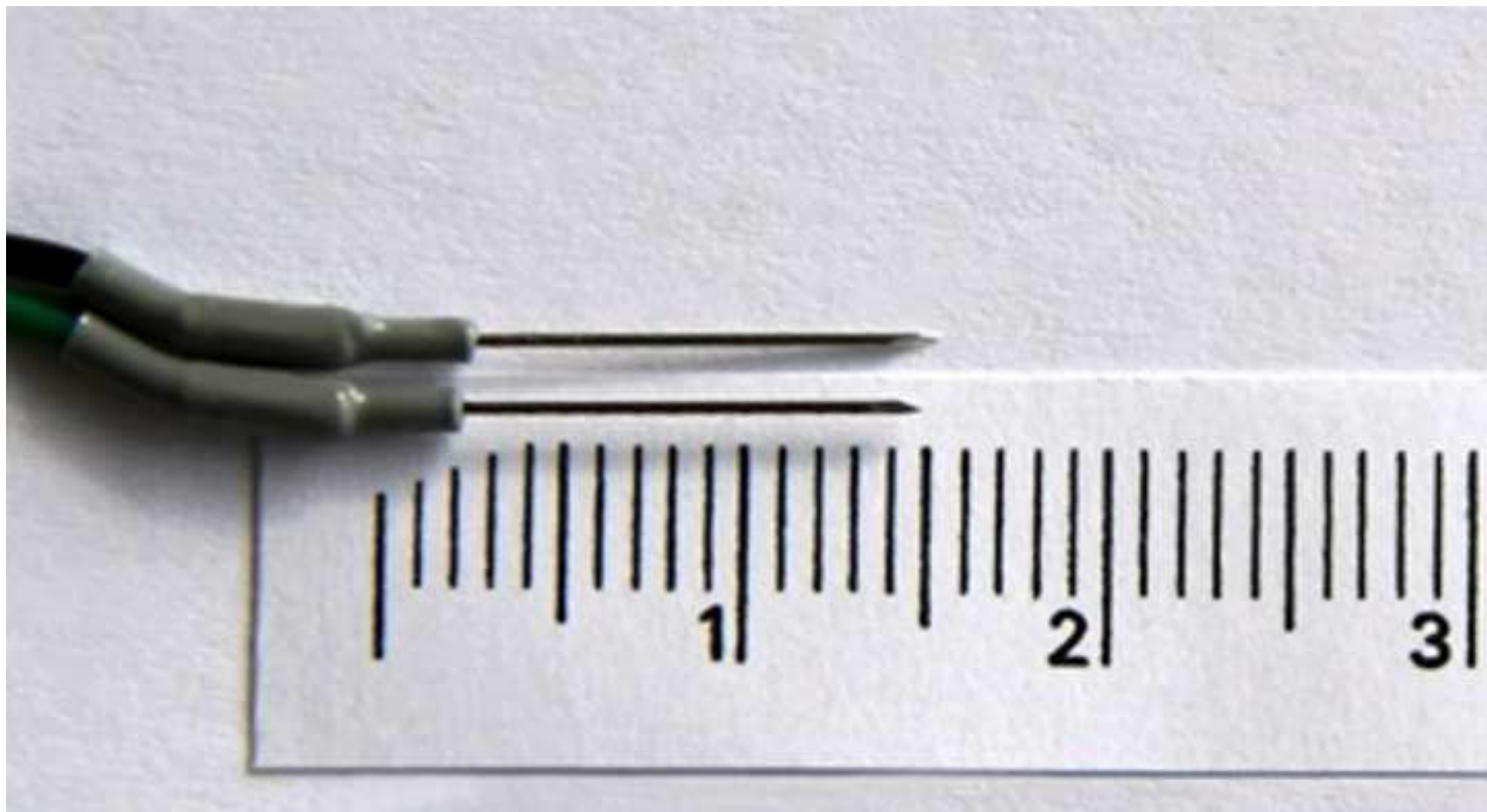


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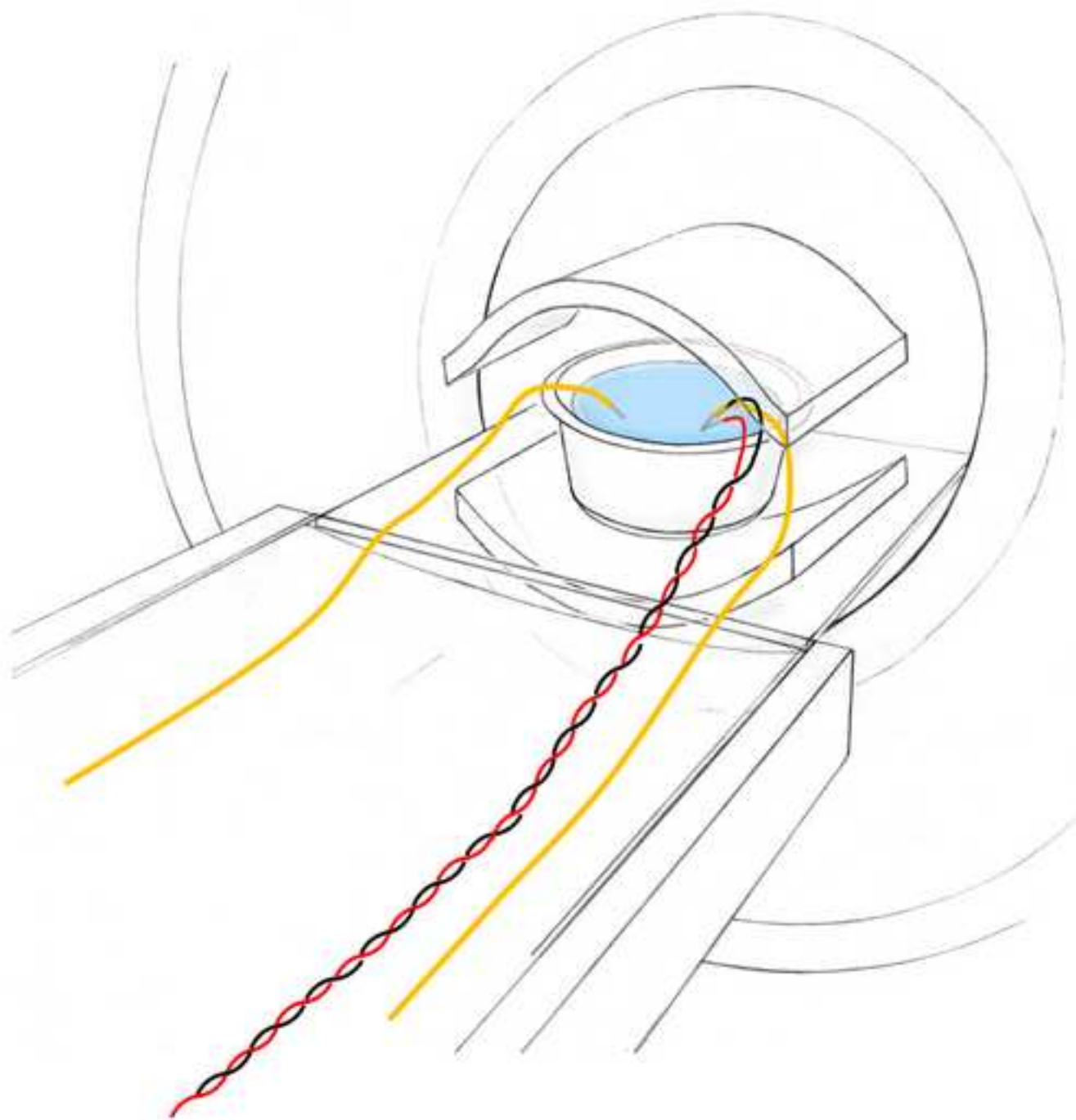
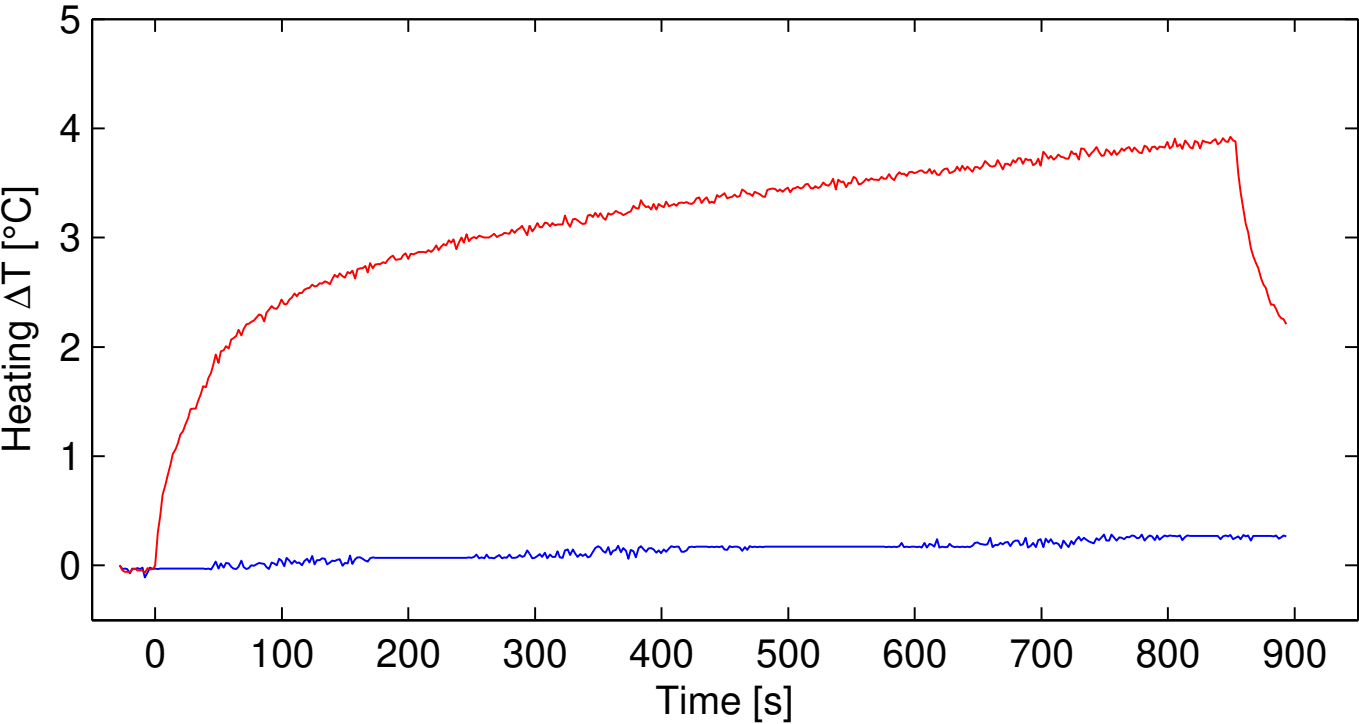


Figure 2 b

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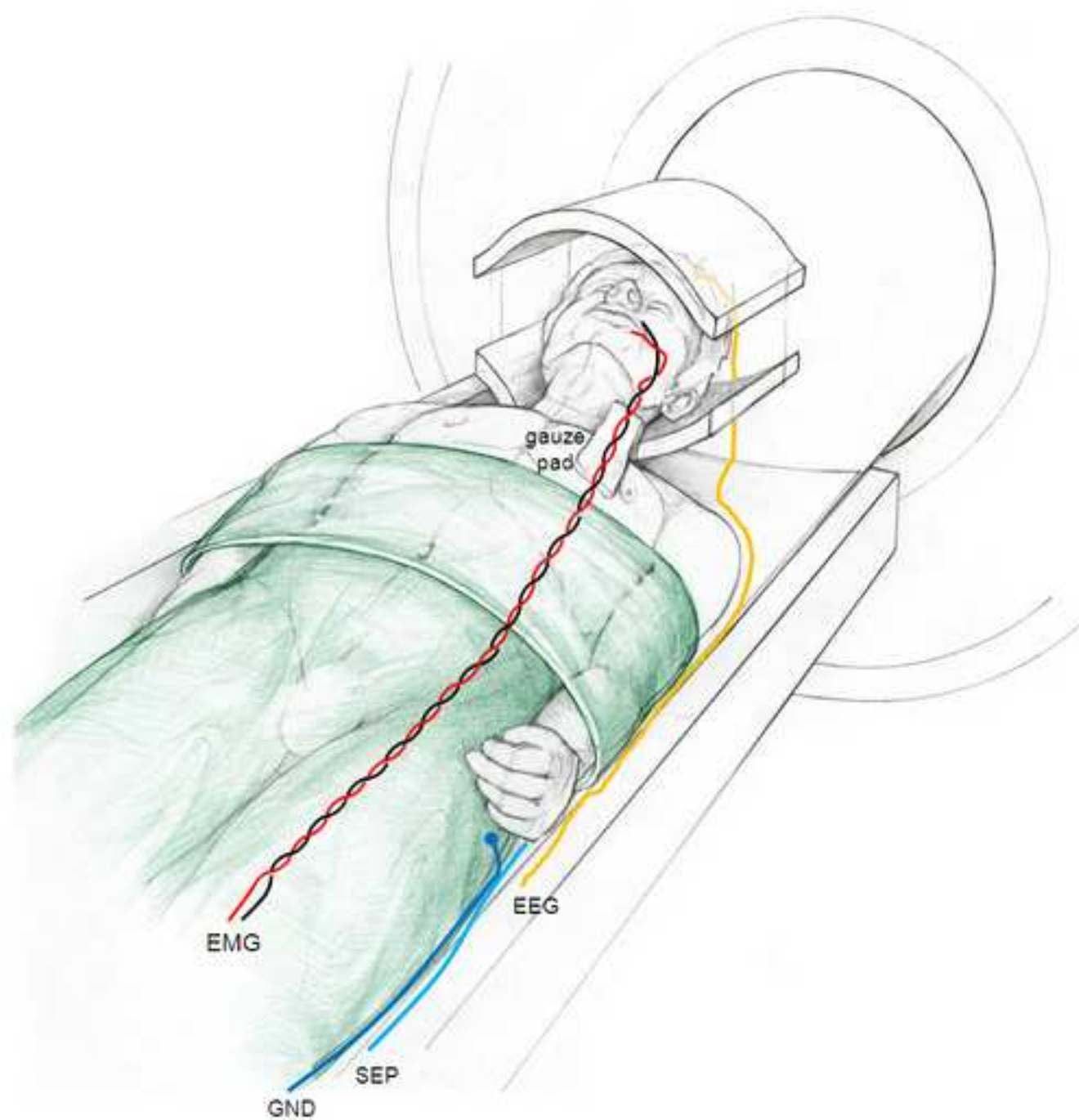




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